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Evaluating the safety impact of employing a dedicated lane for connected and autonomous vehicles on a motorway section

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Abstract

This study aims to analyse the safety impact of employing a dedicated lane during the transition period between manual and autonomous driving. In particular, it (1) identifies the optimal strategy for using a dedicated lane for connected and autonomous vehicles (CAVs) according to the safety perspective, and (2) evaluates the safety improvement caused by employing a dedicated lane while penetrating different levels of automation on the road. Using a microsimulation platform (Aimsun's next), about 20 km of motorway segment is modelled and configured with/without a dedicated lane; with mandatory use for CAVs when the penetration rate is up to 30% and optional use for more than 30%. The safety of several scenarios of mixed fleets of CAV are evaluated using the Surrogate Safety Assessment Model tool and compared at both modelled configurations (with/without a dedicated lane) under both traffic conditions (free flow and congestion). The optimal strategy to employ a dedicated lane at light volumes is when the penetration rate of high levels of automation is above 55% (optional policy) while employing a dedicated lane is always appreciable at congestion condition.

Keywords: connected and autonomous vehicles; dedicated lane; traffic safety; traffic conflicts; CAV

1. Introduction

Dedicated lanes (DLs) have been suggested as a viable scenario for the introduction of connected and autonomous vehicles (CAVs) on the roads. As a result, several studies have recently begun to examine the impact of this option. On one hand, some studies examined the impact at two-lane highway. For example, Chen et al. (2017) investigated the impact of applying three configurations of DL on road capacity at different CAV penetration rates: zero DL, one DL mandatory for human driven vehicles (HDVs), and one DL mandatory for CAVs. Their findings

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revealed that zero DL produced more capacity in this case. Furthermore, they highlighted that traffic volumes on the road, as well as the penetration rate of CAV, are critical factors in restoring the benefit of DL. Mohajerpoor and Ramezani (2019) looked into the effect on traffic delays using four different DL configurations: zero DL, one DL mandatory for HDVs, one DL optional for CAVs, and one DL mandatory for CAVs. Their main findings were that zero DL outperformed DL over the entire transition period to CAV, and the extracted optimum strategy for using a DL was as follows: below 50% of CAVs penetration on the road, to use a DL for HDVs, between 50 and 65%, an optional use of DL for CAVs, and above 65%, a mandatory DL for CAVs was the best option.

The majority of studies, on the other hand, employed the DL configurations on more than two-lane highways. For example, two successive studies (Zhong et al., 2020; Zhong and Lee, 2019) examined the impact of one DL and two DLs on road capacity and stable performance on a four-lane highway at different CAV penetration rates. Their overall conclusion was that when the participation of CAVs on the traffic stream is 40% or higher, one or two DLs outperformed zero DL.

However, the previous studies considered only one definition of CAV (i.e. not considering different levels of automation). Consequently, He et al. (2022) tried to provide wider understanding by applying a comprehensive investigation at various CAV levels and penetration rates on two-, three-, and four-lane highways; allowing only high automation levels (i.e. Level 3 to Level 5) to operate on the DLs. Precisely, they investigated the effects of zero DL, one DL for CAVs (optional and mandatory), and two DLs for CAVs (optional and mandatory) configurations on capacity and throughputs. They underlined that below 50% CAVs penetration rate, implementing DLs for CAVs has no significant advantages on traffic efficiency. If a DL configuration was chosen, the mandatory policy was advised over the optional one. Even so, above 80% CAV penetration rate, the optional policy of DLs performed better.

Nevertheless, concerning the safety impact, there is limited acknowledged evidence-based research about how various deployment conditions (penetration rates and traffic demand) affect traffic safety. According to the authors' knowledge, only one such study with a penetration rate of up to 30% has been conducted previously (Zhang et al., 2020). They tested the zero DL, one DL, and two DLs configurations for CAVs on a four-lane highway to evaluate the longitudinal and lateral traffic safety, and highlighted that: (1) while one DL was capable of improving traffic safety at low traffic volumes, two DLs were required for congestion conditions; and (2) low penetration rates CAV' scenarios negatively affected longitudinal safety.

Moreover, the introduction of various levels of automation as a real-world scenario has not yet been researched in the traffic safety impact context. On this basis, the novelty of the current study is to investigate the traffic safety impact of DL applying various mixed fleet scenarios, penetration rates of CAVs, traffic demand and policies (mandatory/optional) to quantify the safety advantages and to identify the optimal strategy of employing the DL.

The rest of this paper is organized as follows. The second section introduces the case study area, the simulation environment and the safety evaluation approach. The third section presents the main findings of this study discussed with other research works. Finally, the forth section highlights the conclusions of this paper.

2. Simulation-based safety evaluation approach

2.1. Dedicated lane configuration

As a case study, the motorway segment of 20.27 km that was modelled in Miqdady et al. (2023) is reconfigured with a DL to be exposed to comparison with the mentioned study's results as a base condition (0 DL). Regarding the modelling criteria for deploying the dedicated lane, the following policies are applied to be tested:

Basically, according to the previous studies (e.g. Chen et al., 2017; Hamad & Alozi, 2022; Mohajerpoor and Ramezani, 2019; Razmi Rad et al., 2020) that affirmed that using a DL for CAVs on a two-lane sections will not outperform the 0 DL at CAV introduction period, this study does not consider the deployment of one DL configuration on the two-lane sections along the motorway segment. In other words, the configuration of DL is only deployed on three- and four-lane sections. Consequently, the overall length of the sections that are simulated with a DL is 9,038 m in the northern direction and 9,419 m in the southbound direction (i.e. about half of the motorway segment).

In addition, following He et al. (2022), the deployed DL policy is modelled to operate with the simulated high levels of automation (Level 3, L3 and Level 4, L4). Moreover, the applied policy is set according to the penetration rates of these vehicles (L3 and L4 vehicles); if the penetration rate of L3 plus L4 vehicles is up to 30%, the policy is under mandatory use where CAVs can operate only on the DL (Zhang et al., 2020). However, following the results revealed in He et al. (2022) about the efficiency of using the optional use policy for CAVs at high penetration rates, the optional use is modelled (i.e. the CAVs can chose to drive over the DL or the other lanes) if the penetration rate of high levels of automation is more than 30%.

2.2. Microsimulation modelling

Aimsun Next 20 (Aimsun, 2020) with the V2X extension was used in this work to calibrate CAV levels and configure the DL. The preparation of the microsimulation model in this study followed Wunderlich et al. (2019) guidelines which propose that: (1) the fleet scenarios were simulated for one hour using a 0.1 s time step; and (2) the warming up period was calculated to be 18 minutes for the off-peak condition and 25 minutes for the peak condition.

Furthermore, based on data acquired from several detectors set along the route by the General Traffic Direction (Dirección General de Tráfico, DGT), the network information (volume counts, speeds, traffic composition (passenger cars vs. heavy vehicles), etc.) was defined regarding both peak and off-peak conditions by direction (northbound and southbound) to calibrate and validate the modelled motorway traffic operations. See Miqdady et al. (2023) for more details about the criteria used for the calibrated volumes and the validation of the modelled network.

As well, the levels of automation (SAE, 2014) and connectivity were handled (see Miqdady et al. 2023) by calibrating the parameters of Gipps' traffic models (used in Aimsun) and V2X extension before applying various suggested fleet mixed scenarios displayed in Table 1. Table 1 exhibits the composition of each scenario by the percentage of vehicle type: human-driven vehicle (HDV), and the levels of automation from Level 1 to Level 4. The potential percentage of vehicles on the dedicated lane (i.e. L3 plus L4 vehicles) is displayed as shaded columns, and it varied between 5% in scenario A to 75% in scenario F to represent different cases of CAV penetration rates that could be faced on real roads. Afterwards, the statistically significant number of runs for each studied scenario was calculated and 15 replications was the verified number (Miqdady et al., 2023). Again, as explained in the previous subsection, while scenarios A, B, C, D followed the mandatory use policy (for L3 and L4 vehicles), in scenarios E and F, they operated with optional use policy for using the DL.

Table 1. The employed scenarios in testing dedicated lane configurations

Scenario	HDV	L1	L2	L3	L4
A	75%	10%	10%	5%	0%
B	50%	10%	25%	10%	5%
C	40%	15%	20%	15%	10%
D	20%	20%	30%	15%	15%
E	5%	10%	30%	30%	25%
F	0%	0%	25%	40%	35%

2.3. Safety impact evaluation

This study utilized the Surrogate Safety Assessment Model (SSAM) tool developed by the Federal Highway Administration (FHWA) to identify traffic conflicts. While processing a trajectory file (microsimulation output), the SSAM keeps tracking the positions of the vehicles in successive time steps, and two vehicles are reported as an overlapping condition (conflict) if they maintain the same speed and projection up until the proposed time-to-collision (TTC) threshold by the modeller.

Based on our previous investigation (Miqdady et al., 2023), two different TTC thresholds were used; TTC=1.50 s to identify HDV-HDV or CAV-HDV conflicts where the follower vehicle is an HDV, and TTC=0.75 s to identify CAV-CAV or HDV-CAV conflicts where the follower is a CAV. L1 and L2 vehicles are categorised in the first group (TTC threshold =1.50 s) because they both require human intervention while driving and show low levels of automation, whereas CAVs correspond to higher levels of automation (L3 and L4 vehicles), and they applied the second condition (TTC threshold = 0.75 s).

Accordingly, for assessing the traffic safety impact of the DL, the potential conflicts were identified with each applied scenario on both proposed motorway segment configurations (zero DL and one DL) and regarding two traffic demand conditions (peak, off-peak). Consequently, the optimal strategy of using a DL through the CAVs introduction was identified and then, the safety result at each penetration rate stage was discussed

3. Results and discussion

In both peak and off-peak traffic flow patterns, the outcomes of implementing two dedicated lane configurations (zero DL and one DL) are presented in this section. Additionally, the results are presented to show the impact of the DL on the traffic safety of the entire motorway segment as well as on only the sections that configured the DL (the one DL configuration is only applied on the sections of three- or four- lanes in the studied motorway, which involve about half of the segment's length).

3.1. The optimal strategy to employ the DL

The following figure (Fig. 1) shows the conflicts that occurred in both road configurations (zero DL and one DL for CAV) in order to assess when it could be useful from the traffic safety point of view to choose one DL configuration during the transition period between manual and autonomous driving. As shown in the previous section, scenarios A, B, C, D, E, and F, are used in this analysis, with respective percentages of L3 plus L4 vehicles of 5%, 15%, 25%, 30%, 55%, and 75%.

Fig. 1 depicts the effects of one DL configuration on traffic safety during off-peak/peak volumes. The resultant conflicts between zero DL and one DL configurations are shown in the figure, along with the calculated percentage change between these two values for each case. For instance, under scenario A at off-peak conditions, the change caused by using a DL is +793.44% (the number of conflicts increased from 2,637 to 23,560 when one DL is considered).

As shown by the figure, when CAVs are introduced at low traffic levels (off-peak volume), zero DL configuration generally outperforms one DL (i.e., generates fewer conflicts), which is similar in the case of the entire motorway segment as opposed to the case of the only sections configured with a DL (three- and four-lane sections). However, there is a stage when employing a DL above this penetration rate could improve traffic safety on road at this traffic condition, representing an optimal strategy. The optimal action to take in this situation is to configure a DL with an optional policy when the penetration rate of L3 plus L4 vehicles is greater than 55% (scenario E). In terms of traffic efficiency, earlier studies came up with a number of optimum points, regarding CAVs penetration rate, for implementing a DL, including 30% (Hamad and Alozi, 2022), 40% (Zhong et al., 2020), 50% (Mohajerpoor and Ramezani, 2019), and 80% (optional policy) (He et al., 2022). They also concurred that if traffic flow is light, zero DL is a superior configuration especially for low CAV penetration rates.

Additionally, at the 55% point (scenario E), the presence of DL with optional policy registered 41.97% more conflicts at the overall segment than the zero DL. However, when only looking at the three- and four-lane sections that are configured with DL in our case, they registered 27.09% fewer conflicts than the base case (i.e., zero DL), demonstrating the impact of this level of penetration on traffic safety on these sections even though it was unable to improve the traffic safety of the entire segment.

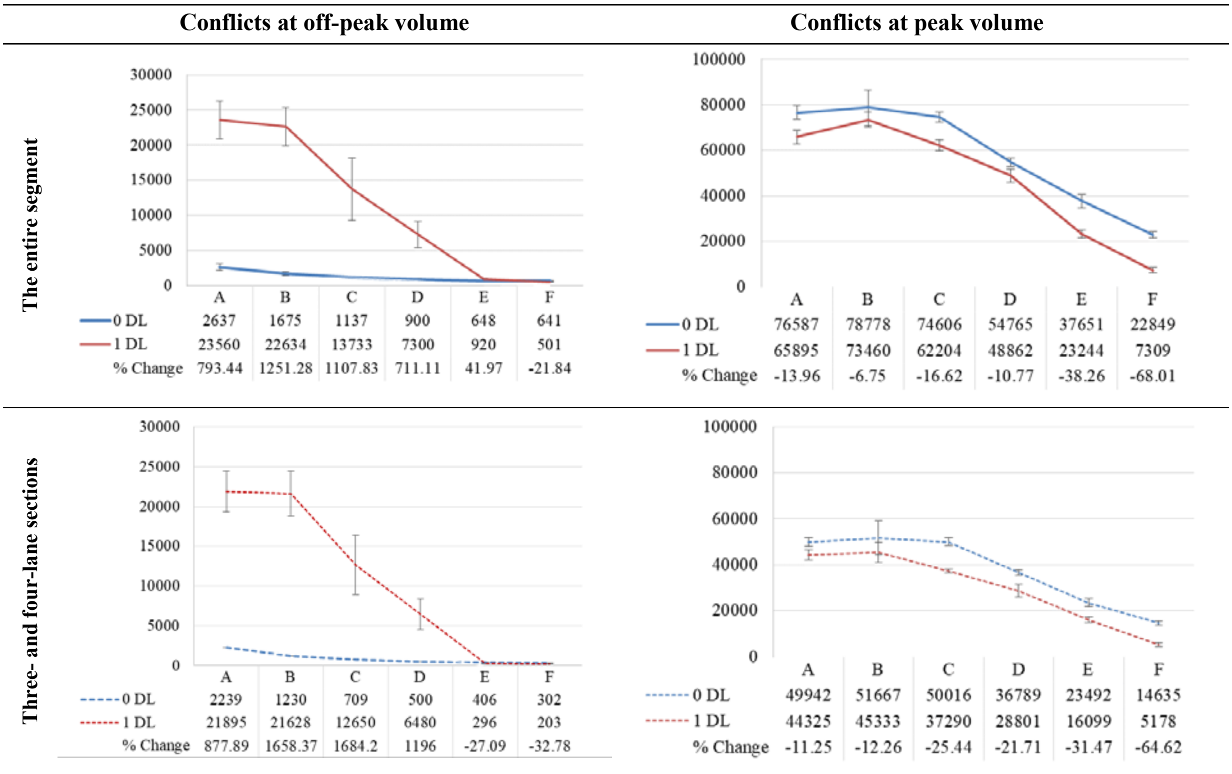

Fig. 1. Comparison of DL configurations in term of potential conflicts at off-peak/peak conditions denoted by (1) the entire segment length and (2) only three- and four-lane sections.

In contrast to the lighter traffic condition, the peak volume (congestion) condition yields a different outcome, suggesting that using a DL could increase traffic safety in all scenarios and under all conditions (i.e. low penetration rates of CAV with mandatory policy and high penetration rates of CAV with optional policy). Notably, the results are consistent for both the entire segment level and the only sections containing DL, with conflicts reduction ranging between 6.75% - 68.01% and 11.25% - 64.62%, respectively.

3.2. DL's safety evaluation among scenarios

This section investigates in depth whether DL is beneficial from the standpoint of traffic safety. To put it more precisely, it enables comparison of the percentage change in the stream conflicts between each scenario and scenario A, which serves as the baseline scenario, demonstrating whether one DL configuration results in greater reduction than zero DL configuration during the CAV introduction period. Once more, the results are broken down by traffic flow conditions as well as by segment as a whole or only the DL-equipped sections (Fig. 2).

The comparison of the off-peak traffic state (zero DL vs. one DL) is shown in Fig. 2. When A is used as the base scenario, the reduction pattern is similar in both the entire segment and only the sections with DL, with lower reduction in the one DL case compared to zero DL at low penetration rates of CAVs scenarios (B and C), and higher reduction in scenarios with higher percentages of CAVs (E and F). However, scenario D shows different outcomes by the sections analysed, one DL provides slightly better safety at the entire segment level, while this is not the case when only sections that have been configured with DL are taken into account. This may be due to that, in scenario D, a large percentage of the vehicles (30%) are operating mandatory in the dedicated lane (as assigned before), which could reach the capacity of the DL and maximum interactions between vehicles, resulting in a minimal improvement in traffic safety regarding the entire segment and slightly diminishing the safety if only the sections deployed by DL are considered. However, when compared to scenario C, the reduction in this scenario still represents a significant reduction (i.e., in C, the reduction is -42.22%, whereas in D, it is -70.4%).

Fig. 2, on the other hand, shows the reduction of the entire segment vs. just the sections with DL in congestion case. A distinct pattern of DL impact is reflected as opposed to off-peak conditions. The safety impact of DL on the entire segment level is not shown up until the segment is operated with high CAV penetration rates (55% and 75%, respectively, in scenarios E and F). An existence of 15% of CAVs on the road (scenario B) reduces the overall safety of the highway in the one DL configuration (the number of conflicts increase respect scenario A). Then, with 25% and 30% of L3 plus L4 vehicles penetration rate on the road (scenarios C and D), operating mandatory on the DL, the safety of the motorway segment in both zero DL and one DL configurations nearly matches. On the other hand, when considering only the sections configured with DL (three- and four-lane sections), a larger reduction due to one DL configuration is visibly apparent. Particularly, the drop begins at a 25% level of penetration rate of L3 plus L4 vehicles (scenario C) on the DL.

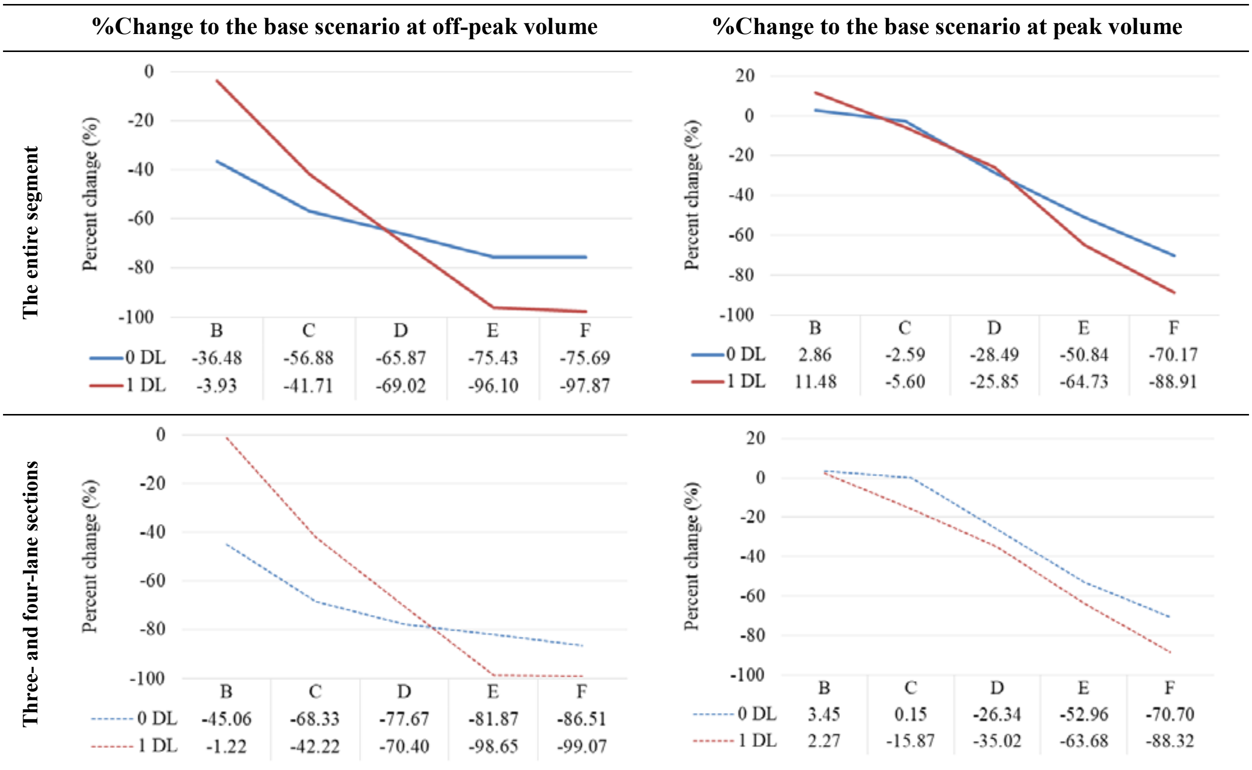

Fig. 2. Comparison of DL configurations in term of %change in conflicts to scenario A (base) at off-peak/peak conditions denoted by (1) the entire segment length and (2) only three- and four-lane sections

The results of Zhang et al. (2020)'s study on the safety impact of DLs with penetration rates of CAV up to 30%, showed that, when using a single mandatory DL configuration, the maximum reduction in potential crash risk in that case (30% CAV penetration rate) reached up to about 53% in off-peak conditions and about 48% in peak conditions. At this amount of CAV penetration (scenario D), however, our data does not demonstrate as better safety gains (Fig. 1), where off-peak condition does not result in any safety gain (711% to 1196% more conflicts) and peak condition demonstrates between 10.77% and 21.71% less conflicts. The reasonable discrepancy between both studies is due to different inputs, including different CAV calibration in traffic flow and lane-change models, the inclusion of all levels of automation in this study while only discussing one level in their study, and, finally, different measures of safety (crash-risk/conflicts) in each study. Practically, they utilized surrogate safety measures that estimate the time that the vehicle is exposed to risk based on the time-to-collision (TTC) integration (e.g. time exposed time-to-collision (TET), and time-integrated time-to-collision (TIT)), whereas the current study employed the TTC for conflict identification as explained in Subsection 2.3.

On the other side, He et al. (2022), who calibrated all levels of automation and penetration rates and implemented various DL policies, comprise the bulk of our analysis, although they examined traffic efficiency no traffic safety. They demonstrated that the most effective strategy to increase traffic efficiency on the roads is to operate a DL with high automation levels at high penetration rates. Additionally, traffic efficiency studies that considered both peak and off-peak traffic volumes confirm that the one DL configuration has a greater impact during peak conditions (congestion) than it does during lower traffic volumes, which generally resulted in the zero DL configuration's superior performance (Chen et al., 2017; Hamad and Alozi, 2022; Zhong et al., 2020).

4. Conclusions

This research provides an analysis of the traffic safety impact of employing dedicated lanes during CAVs introduction. The approach included simulating a motorway segment, calibrating different levels of CAV, and proposing different fleet mixed scenarios, followed by traffic safety evaluation using SSAM. To develop a thorough knowledge of the task at hand, the findings were divided into two steps. The first step provided an optimal strategy to deploy a dedicated lane at the penetration level of high automation levels equal to 55% at low traffic volumes and at any level of penetration at congested traffic condition. The second step shows that, in general terms, the enhancement of traffic safety for dedicated lane increase with higher CAVs' penetration rate if compared to the baseline scenario, however, the great increase comes with high penetration rates in both peak and off-peak conditions.

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